SOME WIND STRESS MEASUREMENTS OVER WAVE SURFACES

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Final Report
U. S. Army Engineer District
Lake Survey
Contract No. DACW 35-68-C-0070

Special Report No. 42
Great Lakes Research Division
The University of Michigan
Ann Arbor, Michigan

1969

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ABSTRACT

Measurements of shearing stress were made over the open water surface of Lake Michigan using an anemometer-bivane as a velocity sensor. The measurements, made on a fixed tower support one mile from shore, include wind speeds up to 13 mps over a range of wave heights. The data indicate a dependency of the wind stress on the wave heights for a given wind speed. These direct measurements of stress show a 0.8 coefficient of correlation with stress estimates made from mean wind profiles during selected cases although a factor of two is observed in scatter about the least squares regression.

ACKNOWLEDGMENTS

The research reported herein has been accomplished with the assistance of other groups. The U. S. Army Engineer District, Lake Survey provided the tower facility, and installed and maintained the wave recording equipment. The assistance of personnel from that group and from the Grand Haven Boat Yard is gratefully recognized.

Mr. Eduardo Michelena, Graduate Student and Research Assistant at The University of Michigan assisted in the instrumentation of the tower, execution of the measurement program, and reduction of the data.

1. INTRODUCTION

In a recent survey "Mechanics of the Air-Sea Interface" Stewart (1967) concludes that "Not only does there remain very large disagreement concerning the magnitude of the wind stress, but the trend remains uncertain." In this statement, reference is made to the present state of knowledge of the relationship between wind stress on a water surface and wind speed at a given height with reference to the quiet surface. A summary of the results of experimental measurements has been presented by Roll (1965) and document the wide variability cited by Stewart. While it may be possible to dismiss the variability of many of these results as due to experimental error or poor exposure of instrumentation, it seems unlikely that all the discrepencies can be so accounted for even with consideration of the inherently difficult problem of making measurements over a water surface.

The largest number of wind stress estimates have been made from mean wind profile measurements by applying models that are known to give consistent results over rigid boundaries. A summary of the results of several investigations of this type is presented by Kitaygorodskiy and Volkov (1965) and show the usual variability. The results cited by Stewart (1967) are, however, of recent direct measurements of momentum flux by modern instrumentation and a consistent trend in the relationship is still not demonstrated. There remains, therefore, to be explained why the wind does not exert a uniform stress relationship over a water surface.

Gerritsen (1963) and Kitaygorodskiy (1968) and Volkov (1965) have made attempts to include measures of surface roughness and of mobility of the roughness elements as additional variables to explain wind stress relationships. It was shown that inclusion of a measure of wave phase velocity would improve the relationship between wind stress and wave height. This result, however, poses the question of which components of the wave spectrum should be considered in that the phase velocity is a unique function of the wave length. Thus, as stated by Kitaygorodskiy, the effective roughness of a water surface must depend not only on the wave heights but also on the spectral distribution of wave energy. If this dependency is valid and the dominant waves are principally responsible for the drag, as assumed in the above work, then it follows that a relationship between wind speed and surface stress will not be unique except under conditions of equilibrium between sea and wind. Such conditions may not be attained in a large portion of the experiments from which data have been reported. In most cases the investigator has little information on the wave and wind history and is not able to evaluate the degree of equilibrium that existed during the actual short period of observation. Kitaygorodskiy and Volkov (1965) has actually shown that, for the data considered, the roughness is nearly a random function of the friction velocity. This would seem to imply that the data were collected under nearly random degrees of equilib-

rium between wind and waves.

The disucssion to this point has not considered the influence of the wave generation processes on the wind velocity profile. As Stewart (1961) implied, the removal of energy from the lower atmospheric layers by the Miles wave generation mechanism would require curvature of the logarithmic wind profile if the mechanism is operational. While conclusive evidence to support this mechansim is as yet lacking, wind profiles qualitatively in agreement with that required have been reported by Takeda (1963) and have been observed on Lake Michigan in the present series of measurements. See Elder and Soo (1967). Under such conditions, the wind profile measurements, if made in the Miles "matched layer," i.e., the region in which the wave velocity equals or exceeds the mean wind speed, will yield values of friction velocity which are not constant with height. This factor may also account for some of the variability in observational results.

The goal of the present program was aimed towards development of measurement methods that would permit accumulation of sufficiently long periods of stress measurements over deep water wave surfaces to allow determination of wind stress relations as functions of nonequilibrium conditions and to test if constant relations are achieved at equilibrium.

2. MEASUREMENT PROGRAM

Until the uncertainties in the profile models for stress determination over water are resolved, reliable measurements must be made by use of the eddy correlation technique. This requirement has restricted measurement to sensitive, complex, and usually delicate instrumentation which produce data requiring extensive processing. The observations have, therefore, been largely restricted to relatively short periods and are most often made near to shore over small shoaling waves.

It is apparent that measurements must be made over deep water waves for extended periods of time if the relationships between the wind stress and sea are to be determined. Such measurements require durable instrumentation that can give acceptable accuracy and can provide data in a form not requiring a prohibitive amount of processing to obtain the desired results.

Instruments that have been employed for direct stress measurement that approach the above requirements include the thrust anemometer as described by Doe (1963), the anemometer-bivane, one version of which is described by Hewson et al. (1962), or the triaxial configuration of propeller anemometers such as described by Holmes et al. (1964). Each of these instruments have limited upper frequency response and, with the exception of the thrust anemometer, certainly do not measure the total momentum flux. Smith (1967) has shown, through comparative measurements with hot wire anemometers, that the thrust anemometer can successfully measure the momentum flux at heights of 1 to 5 meters over a water surface. Similar evaluation of the other instruments which are more rugged and, in that sense, more desirable, has not been accomplished to the author's knowledge.

Anemometer-bivanes have been employed in the present program and some results reported by Elder and Soo (1967). It was shown that this instrument can obtain useful measurements but the degree of attenuation at higher frequencies remains in doubt. In addition the anemometer-bivane and the direct application of propellers retain the requirement for relatively high frequency recording. Work over the past several years by the staff of C. W. Thornthwaite Associates has been devoted to development of a direct flux measurement system that would eliminate a major portion of the data processing and would give an immediate measure of the flux integrated over a chosen time period. A description of this development is contained in reports by Thornthwaite, et al. (1961, 1962), and by Field and Superior (1964). The instrument has been used for extended periods at the Argus Island Tower facility of the U.S. Naval Oceanographic Office but has not been subjected to evaluation by direct comparison to fast response instruments.

The present program was planned to obtain simultaneous measurements of

momentum flux over a deep water wave surface by use of a modified Thornthwaite momentum flux meter, a bivane anemometer and, through cooperative arrangements with another program, a hot wire anemometer. Documentation of the wind and temperature profiles and of the wave characteristics were also to be obtained.

2.1. INSTRUMENTATION

Measurements were carried out on the U. S. Lake Survey, Lake Michigan Research Tower located in 15 meters of water, about one mile from shore near Muskegon, Michigan. The tower has been described in previous reports, Elder and Soo (1967), and is shown in Figure 1. Sensors were mounted on arms extending westward from the tower so that the tower influence was a minimum for air flow off the lake. Recording equipment was mounted on the platform above the 10 meter elevation. Power was supplied to the tower by submarine cable from shore.

Use of the anemometer-bivane, shown in Figure 2, has been previously described by Elder and Soo (1967). Two of these instruments were used, mounted at levels as indicated in the discussions and extending 6 feet from the tower. The data were recorded on an Ampex SP-300 analog tape recorder using parallel channels to record simultaneously the data from two bivanes and the wave height.

A modified form of a momentum flux meter as described by Thornthwaite (1961) was constructed from components available to the program. The sensors, shown in Figure 3, consisted of a sensitive cup anemometer to measure the horizontal wind and a vertically oriented propeller to sense the vertical wind component.

Digital logic was designed to accumulate the vertical and horizontal travel of the wind on electromechanical counters. On command, the counters printed the accumulated values on tape for later computation and analysis.

The unit was assembled and ready for testing late in the measurement season so that a complete performance test was not possible. It was mounted on the research tower in late September but was never fully operational. Due partially to an error in logic specification and due to malfunction of the electromechanical counters, significant data were not obtained. The logic circuit employed, which was incorrect, is not reproduced here. The reader is instead, referred to the report by Field and Superior (1964). Further discussion of the instrument is included under discussion of results.

Mean temperature gradient in both air and water were measured by use of differential thermocouples using the near-surface water temperature as reference. The data were recorded on a multipoint potentiometer recorder having a resolution of about 0.01°C. Absolute temperature of the water near 15 meter depth and of the air at 15 meter elevation was measured by a thermistor and recorded to a resolution of about 0.05°C. The error of the absolute measure-

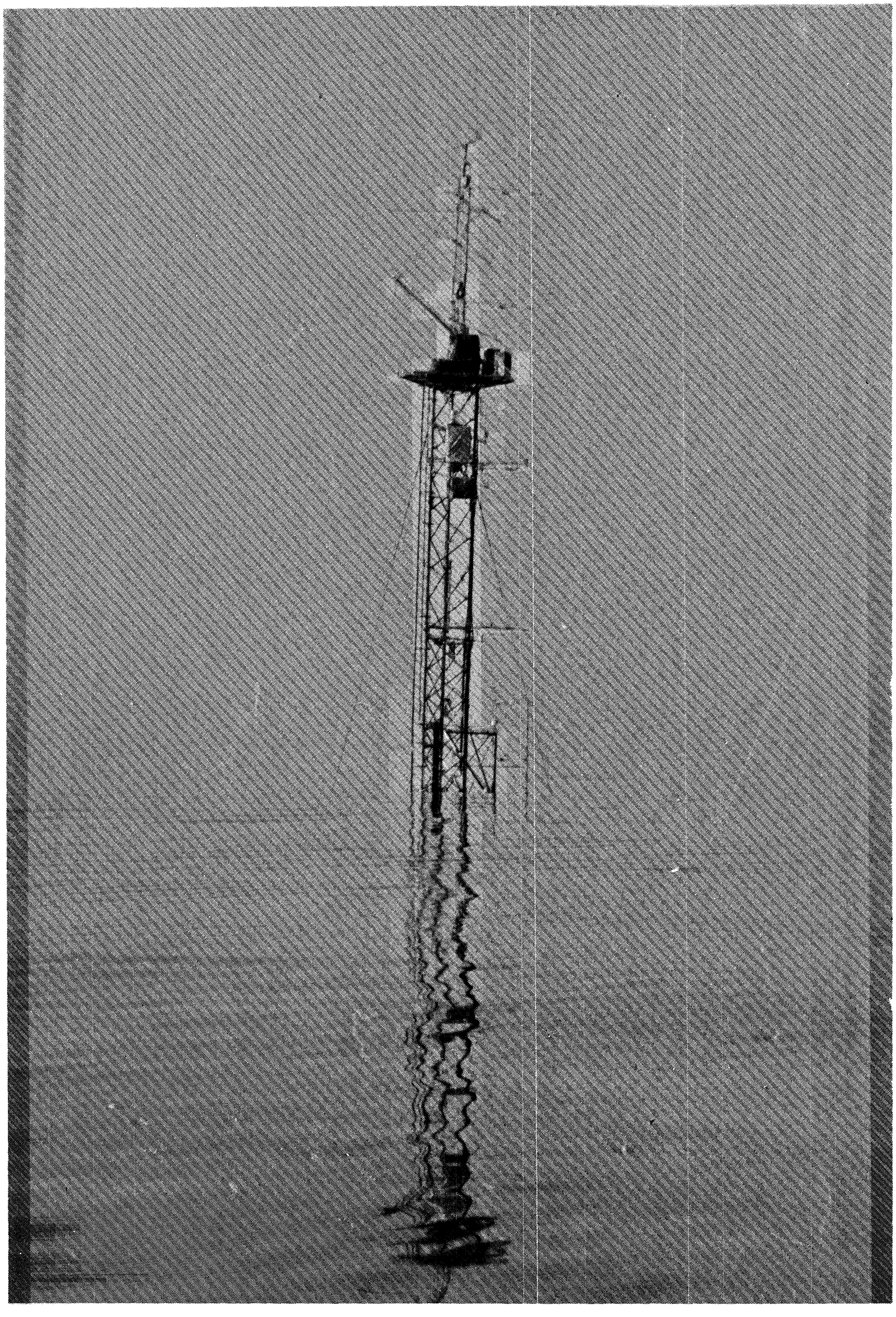


Figure 1. U. S. Lake Survey, Lake Michigan Research Tower.

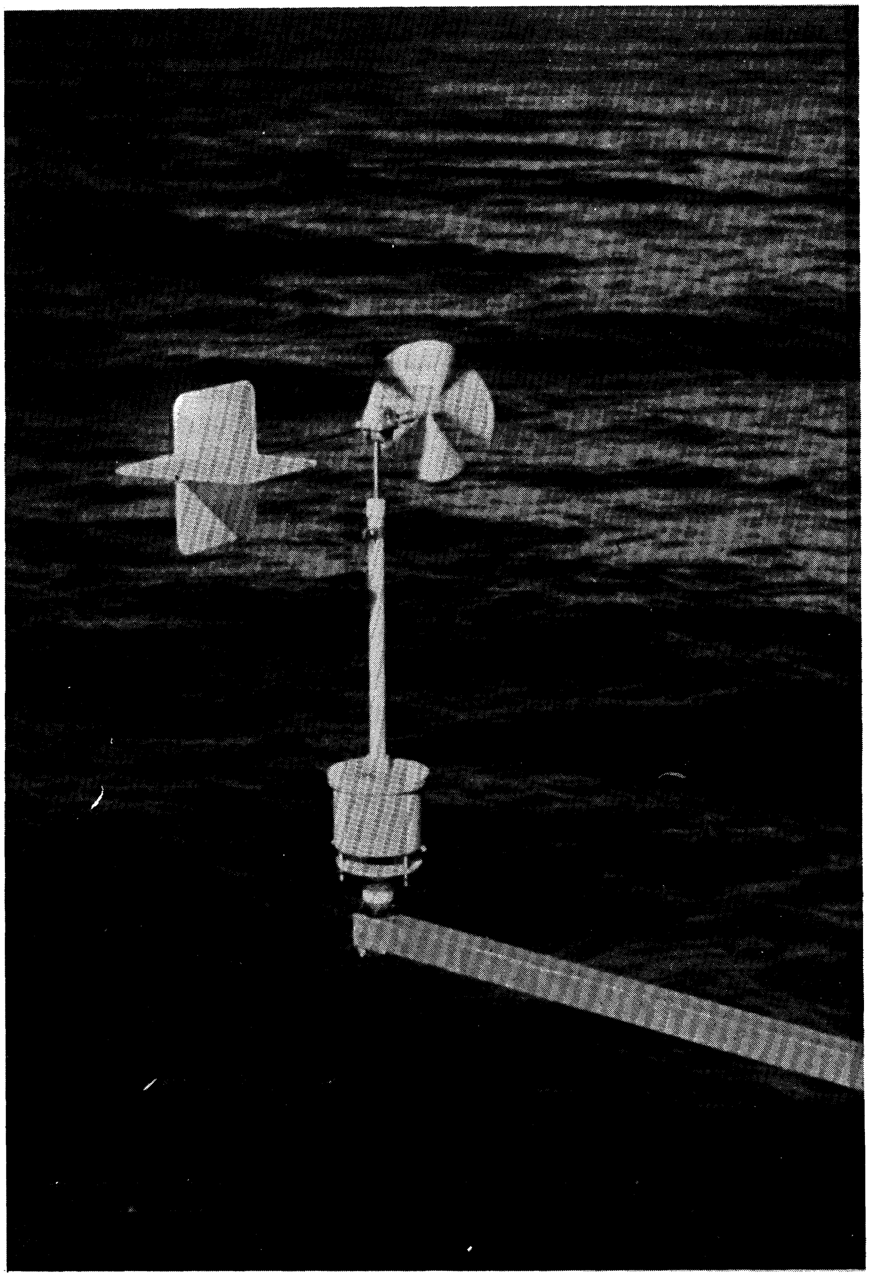


Figure 2. Anemometer-bivane.

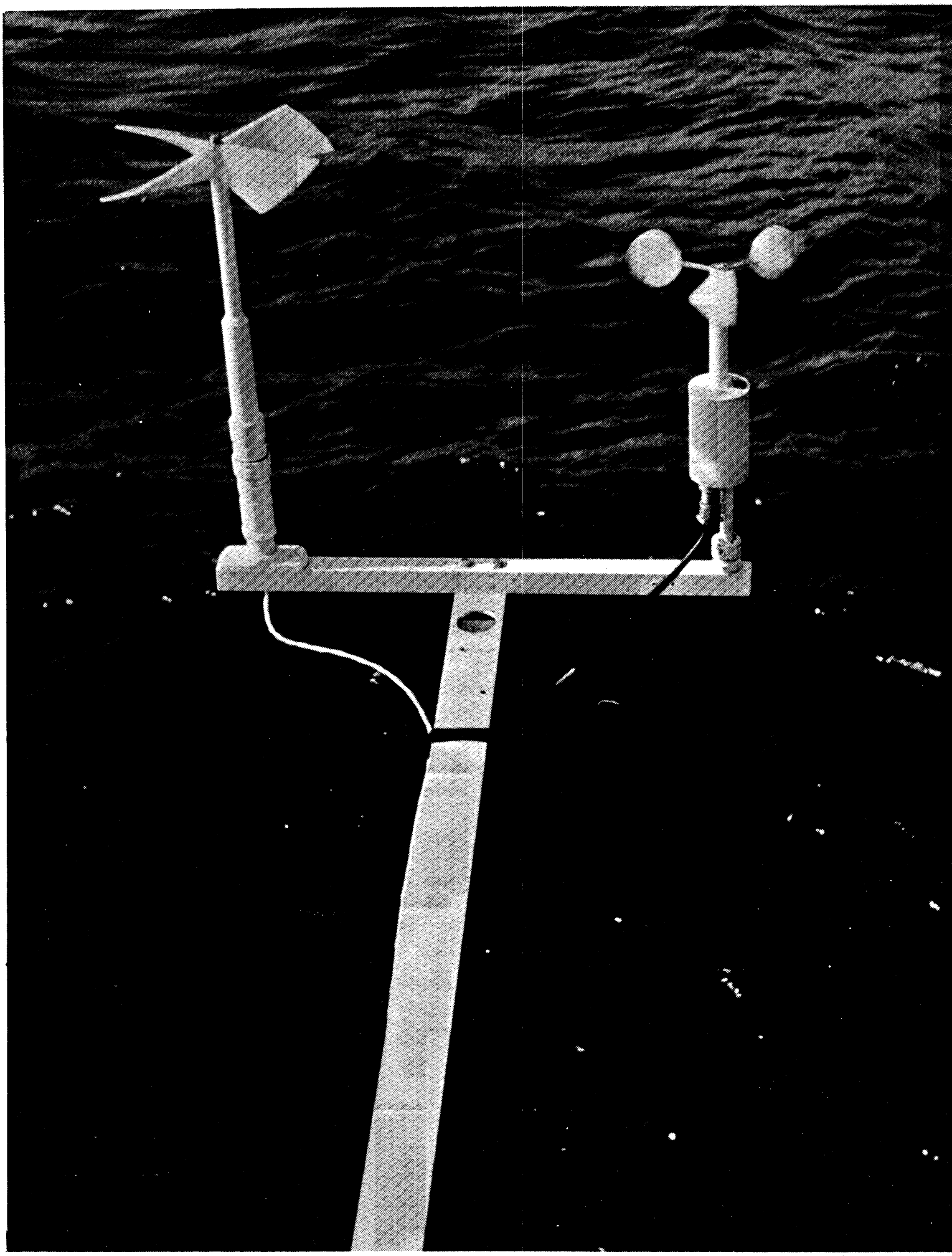


Figure 3. Horizontal and vertical sensors of momentum flux meter.

ments cannot be stated exactly but is estimated to be less than 0.5°C.

Vertical gradient of mean wind speed was measured by sensitive three cup anemometers mounted on an approximately logarithmic spacing from 1 to 15 meters. The data were recorded on an operations recorder in the form of individual anemometer cup revolutions. These records are available to sum over selected time periods to obtain mean wind passage at the given heights. Wind records were usually obtained only during those periods when other flux measurements were being made because the rate of chart usage was prohibitive for full time recording.

Hot wire anemometer measurements were made under a separate contract by personnel working under the direction of Professor Donald J. Portman. Observations were made coincident with anemometer-bivane observations on several cases and, while they are not reported herein, will be available for later comparison.

Other measurements made during several of the periods of flux measurement include the three-dimensional flow in the wave zone at a depth of about 2 meters. The triaxial flow meter as described by Elder, Michelena, and Soo (1967) was employed giving an analog of the orbital velocities in the wave zone. The data were recorded on the magnetic tape recorder, replacing one bivane record during these periods.

A continuous record of wind velocity at the 16 meter level of the tower was obtained from a Bendix Aerovane wind system. These data are essentially continuous with the exception of brief periods of recorder chart malfunction.

3. REDUCTION AND PROCESSING OF OBSERVATIONAL DATA

Complete processing and analysis of the observational data has not been completed as of this writing and was not proposed as part of the original program. The mean profile measurements have been reduced only to obtain stability criteria and stress estimates for the periods for which bivane data are analyzed. Hot wire measurements are not dealt with in this report.

3.1. MOMENTUM FLUX METER MEASUREMENTS

As stated above, the momentum flux meter was not completed early enough in the program to permit thorough check out and testing. It was operated on the research tower for a total of about 7 days, but out of this period only a few hours of data were obtained when the electromechanical counters functioned properly. Inspection of these periods do, however, indicate other problems with the instrument as here employed.

As developed by Thornthwaite, et al. (1962), the vertical shearing stress may be stated by,

$$\tau = -\rho\,\overline{w'u'} = \rho\,\bar{w}\,\bar{u} - \rho\,\overline{wu} \qquad (1)$$

where τ = shearing stress (positive downward)

ρ = air density

w = vertical velocity component

u = horizontal velocity component

The "eddy" stress is, therefore, represented as the difference between the total stress and the stress carried by the mean flow.

Evaluation of the two terms on the right of equation (1) requires the simultaneous measurement of the horizontal and vertical velocity components. It is at this point that usual measurement techniques require elaborate recording equipment and extensive data processing.

The fluxmeter as described by Field and Superior (1964) involves a sampling of the horizontal wind and summation of the momentum transferred in the up and down directions. These sums may be accumulated over chosen periods and used to evaluate the right of equation (1). Data processing is nearly elim-

inated and the unit should be capable of extended operation.

The system that was assembled was planned to obtain information for evaluation of equation (1) over 10 minute periods. Two factors prevented obtaining of satisfactory data. As stated above, the mechanical registers failed to function reliably so that all results are subject to doubt. Also, an error was made in the logic specification so that values of w and u were summed rather than values of wu for both up and down transport. It appears that this would not completely invalidate the data but the results obtained are unrealistic.

A third problem arises in the exposure of the vertical wind sensor. The propeller anemometer has a response such that the velocity component parallel to its axis of rotation is measured. If exposed with its axis vertical, it thus measures the vertical wind component. If, however, the axis is inclined from the vertical, a portion of the horizontal component wind is measured. Since the horizontal wind greatly exceeds the vertical component, a small tilt in the mounting of the vertical anemometer results in very large errors. This factor is important when the equipment is used on towers in that exact leveling is usually difficult. There is evidence in the data accumulated that leveling may have been in error in that $\bar{w}$ had large values which would not be expected.

These factors do not amount to rejection of the system for momentum flux measurement. No valid tests were obtained due to failure of the equipment, the technique appears yet to offer the most practical approach to continuous measurement of wind stress over water.

3.2. ANEMOMETER-BIVANE MEASUREMENTS

Anemometer-bivane measurements were recorded as analog records of the total wind speeds, azimuth, and elevation. These records are obtained from the two instruments on parallel channels of a single magnetic tape recorder and therefore retain phase relationship for later analysis. It is necessary to translate the data into the three orthogonal velocity components prior to computation of the cross products for momentum flux evaluation. The required translations are:

$$w = V \sin \Phi$$

$$u = V \cos \Phi \cos \Theta$$

$$v = V \cos \Phi \sin \Theta$$

where

w = vertical wind component

u = horizontal down stream wind component

v = horizontal cross stream wind component

V = total wind speed

Φ = elevation angle

Θ = horizontal angle

Some high frequency signals are usually present in the records due to contact noise or to electronic interference. In addition to the translations, filtering of this noise is desirable prior to analysis.

The translation and filtering were both accomplished on an analog computer prior to digitization for computation. Since, as discussed by Elder and Soo (1967), the bivane response is limited to approximately 1 Hz in a 10 mps wind, it was decided to terminate the data at about 2 Hz. The data of all channels were filtered through active filters having a filter function as shown in Figure 4. Noise of frequency greater than about 10 Hz was attenuated by 50% or greater while the signal at 1 Hz was unattenuated and should have suffered no significant phase shift.

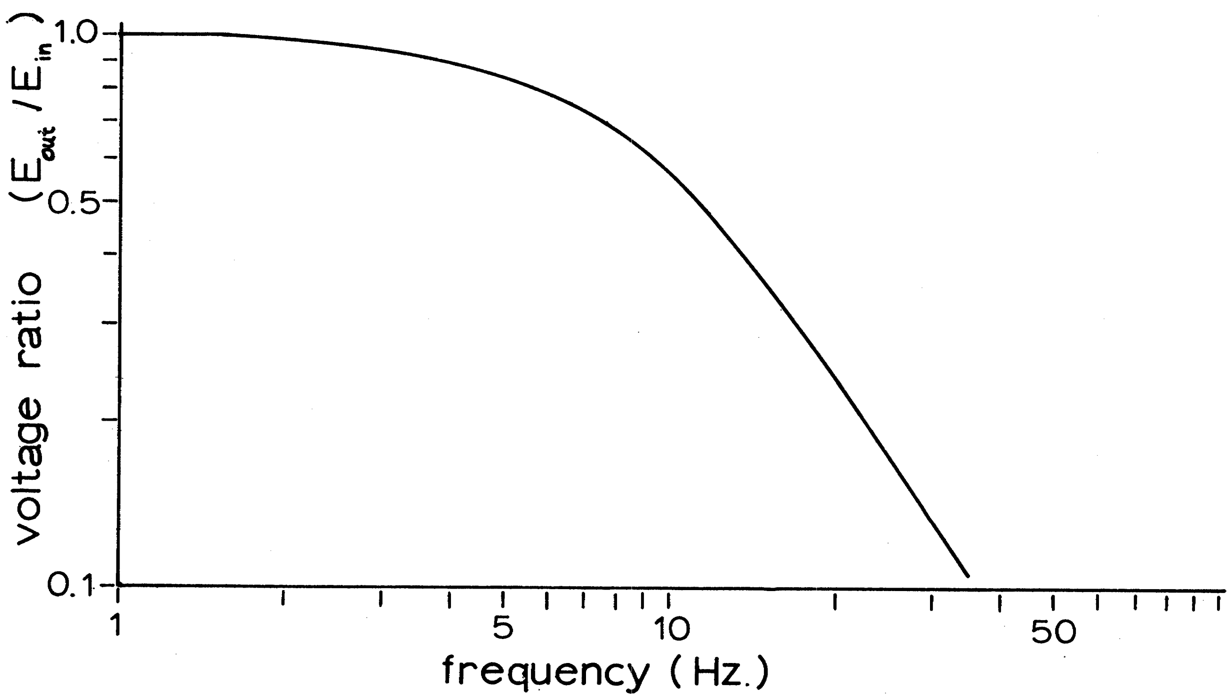


Figure 4. Frequency response curve of data filter.

Sine-cosine function generators were employed to perform the necessary translations. Gains were adjusted to provide convenient scales and the data were output to a seven channel digitizer. The data were then written sequentially in binary format on magnetic tape compatible to machine processing. Digital sampling was accomplished at a rate of two points per second.

Wave height and flowmeter data were digitized in a similar manner when those records were contained in place of a second bivane record on the magnetic tape.

3.3. MEAN TEMPERATURE AND WIND PROFILES

The mean temperature profiles were recorded on a Honeywell Electronik 15 multipoint strip chart recorder. For periods when momentum flux measurements were made, temperature profiles were taken once every two minutes, otherwise once every six minutes. The 15 meter air temperature and -16 meter water temperature were measured by YSI Thermilinear Thermistors. The temperature difference between water surface and 15 meter, 12 m, 8 m, 4 m, 2 m, 1 m, 0.5 meter above water surface, as well as the temperature difference between surface and 2 meter, 4 m, 8 m, and 16 m below water surface, respectively, were measured by using thermocouples allowing resolution to .01°C.

For the purpose of defining stability, only 15 meter air temperature, water surface temperature and temperature differences between 15 and 4 meters were read from the charts and tabulated for selected periods when we have anemometer-bivane measurements. The Richardson Numbers (Ri):

$$Ri = \frac{g}{T_{15}} \frac{\Delta T \ \Delta Z}{(\Delta U)^2}$$

ΔT = Temperature at 15 meters - temperature at 4 meters

ΔZ = 15 meters - 4 meters

ΔU = Wind speed at 15 meters - wind speed at 4 meters

T_{15} = Absolute temperature at 15 meters (°K)

were calculated for six minute averages and plotted along with the six minute wind profiles.

The wind profiles were recorded on an Esterline-Angus Events recorder in the form of a count for each revolution of cup rotation. For periods corresponding to anemometer-bivane measurements, counts per six minutes of recording were read off the charts and converted to average wind speeds for each level. Correction factors were applied to each anemometer as determined by comparison tests made on the set of anemometers used. The resultant profiles were plotted on Figures 5 a-e.

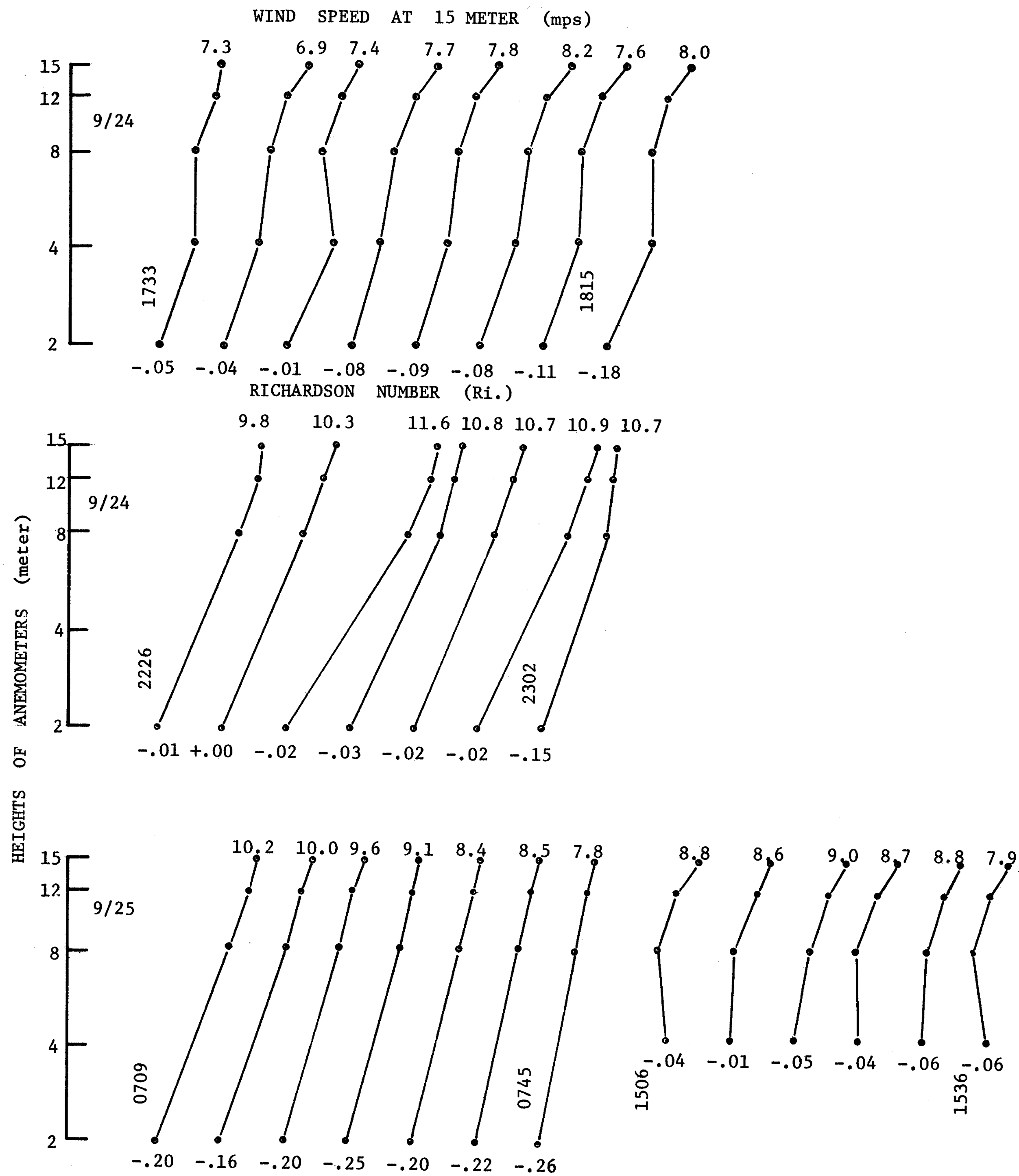
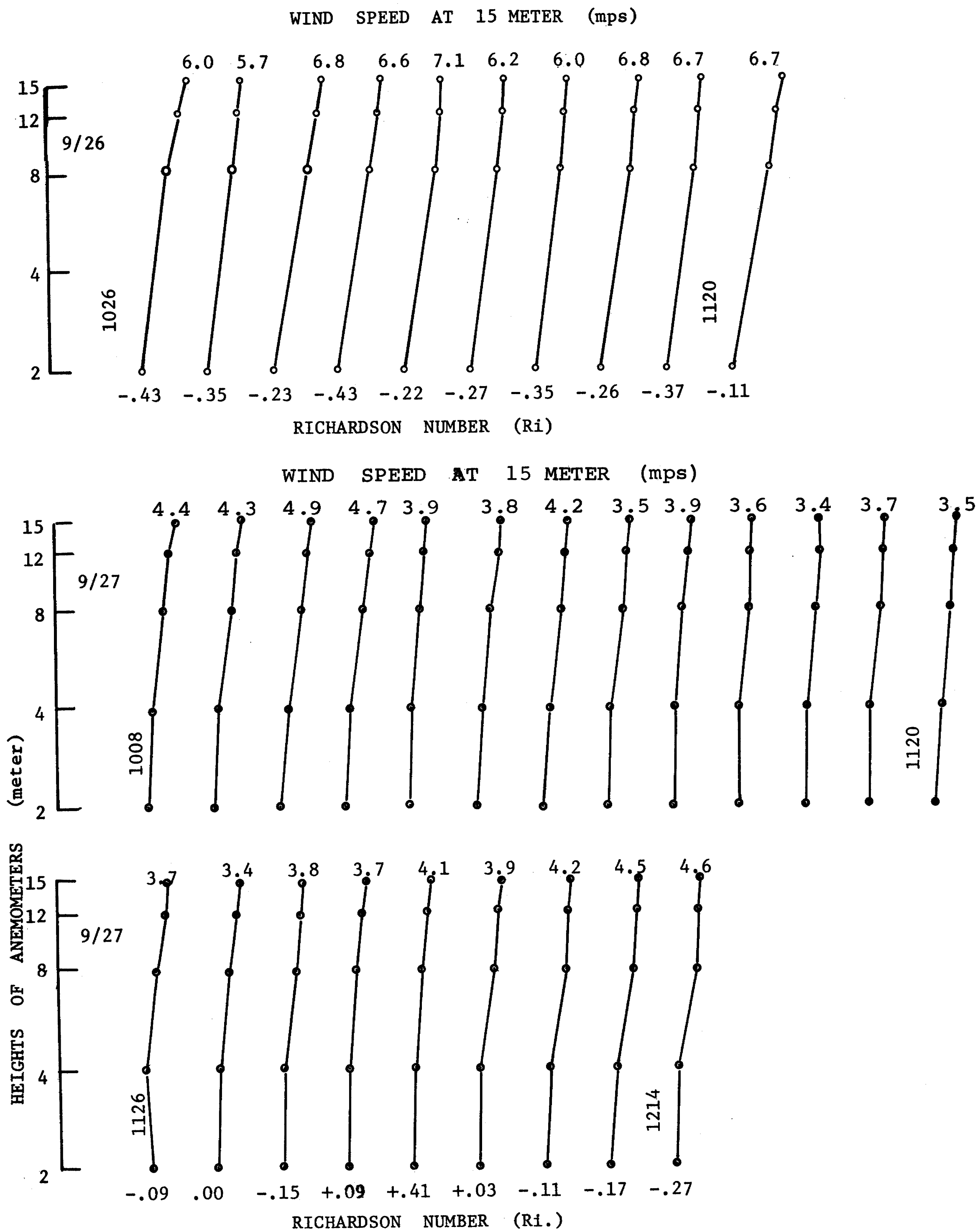
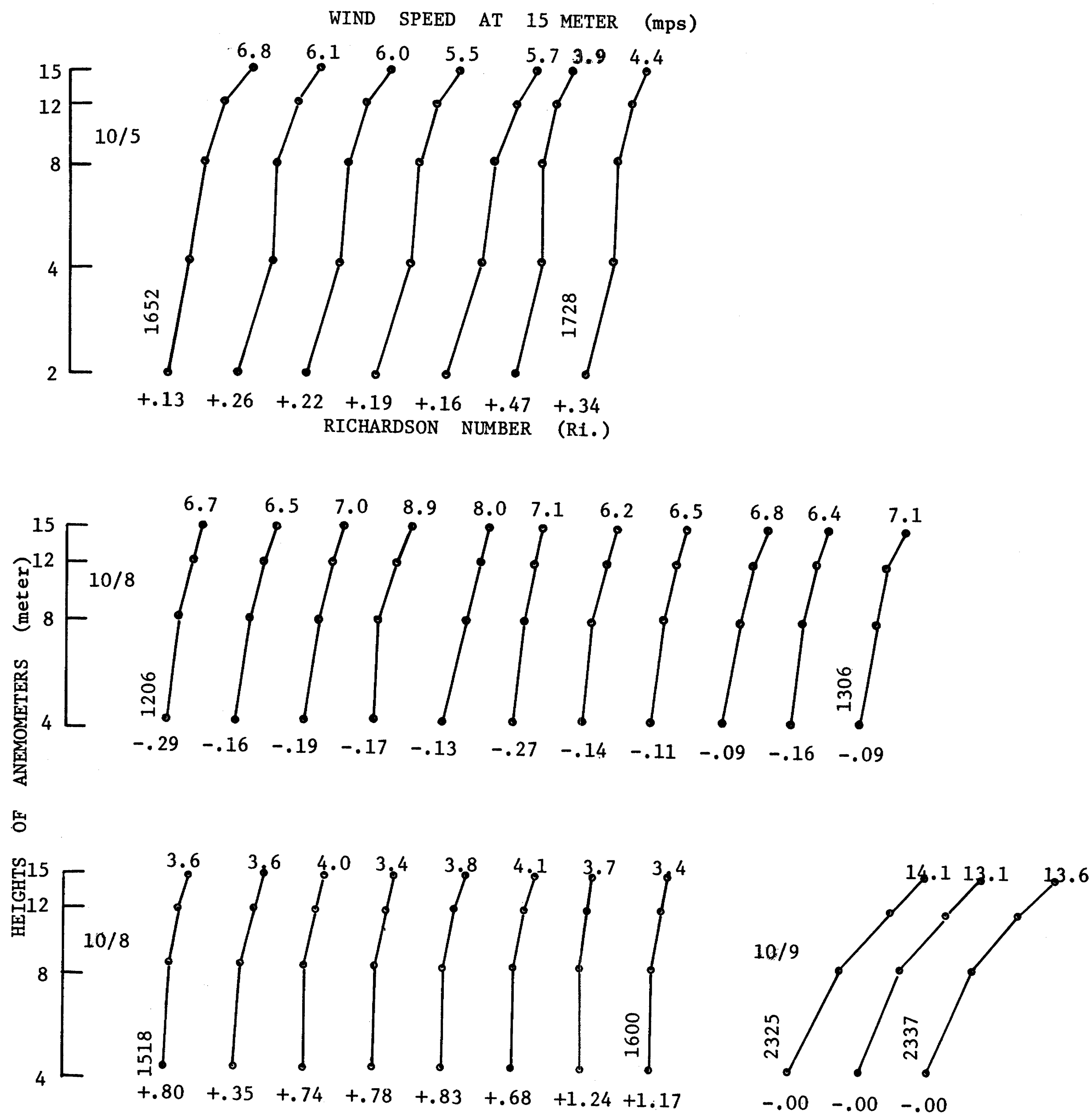
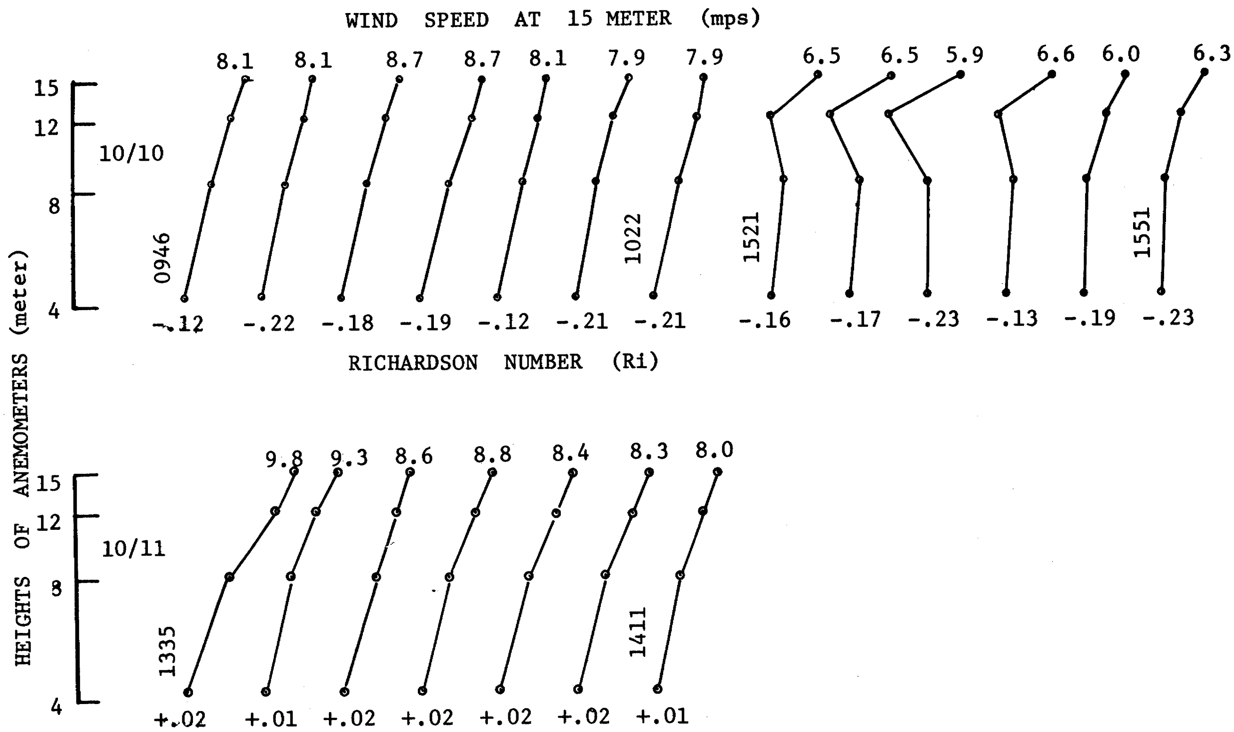


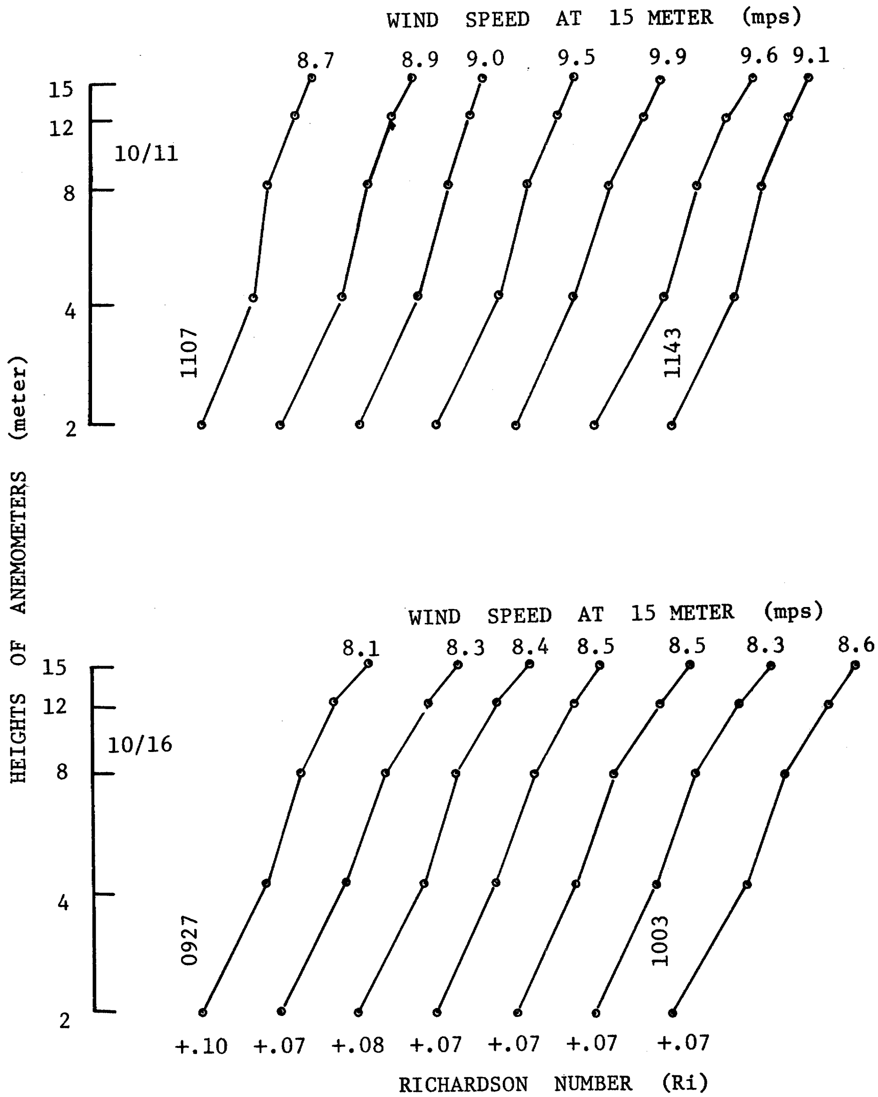
Figure 5. Wind profiles for selected periods, fall, 1968.



WIND SPEED AT 15 METER (mps)
6.0 5.7 6.8 6.6 7.1 6.2 6.0 6.8 6.7 6.7
15
12
9/26
8
4
2
1026
1120
-.43 -.35 -.23 -.43 -.22 -.27 -.35 -.26 -.37 -.11
RICHARDSON NUMBER (Ri)
WIND SPEED AT 15 METER (mps)
4.4 4.3 4.9 4.7 3.9 3.8 4.2 3.5 3.9 3.6 3.4 3.7 3.5
9/27
1008
1120
HEIGHTS OF ANEMOMETERS (meter)
3.7 3.4 3.8 3.7 4.1 3.9 4.2 4.5 4.6
9/27
1126
1214
-.09 .00 -.15 +.09 +.41 +.03 -.11 -.17 -.27
RICHARDSON NUMBER (Ri.)


WIND SPEED AT 15 METER (mps)
6.8 6.1 6.0 5.5 5.7 3.9 4.4
15
12
10/5
8
4
1652
1728
2
+.13 +.26 +.22 +.19 +.16 +.47 +.34
RICHARDSON NUMBER (Ri.)
6.7 6.5 7.0 8.9 8.0 7.1 6.2 6.5 6.8 6.4 7.1
15
12
10/8
8
1206
1306
4
-.29 -.16 -.19 -.17 -.13 -.27 -.14 -.11 -.09 -.16 -.09
HEIGHTS OF ANEMOMETERS (meter)
3.6 3.6 4.0 3.4 3.8 4.1 3.7 3.4
15
12
10/8
8
1518
1600
4
+.80 +.35 +.74 +.78 +.83 +.68 +1.24 +1.17
14.1 13.1 13.6
10/9
2325
2337
-.00 -.00 -.00


WIND SPEED AT 15 METER (mps)
8.1 8.1 8.7 8.7 8.1 7.9 7.9 6.5 6.5 5.9 6.6 6.0 6.3
15
12
10/10
8
4
0946
1022
1521
1551
-.12 -.22 -.18 -.19 -.12 -.21 -.21 -.16 -.17 -.23 -.13 -.19 -.23
RICHARDSON NUMBER (Ri)
HEIGHTS OF ANEMOMETERS (meter)
9.8 9.3 8.6 8.8 8.4 8.3 8.0
10/11
1335
1411
+.02 +.01 +.02 +.02 +.02 +.02 +.01


WIND SPEED AT 15 METER (mps)
8.7
8.9
9.0
9.5
9.9
9.6
9.1
15
12
10/11
8
4
1107
1143
2
HEIGHTS OF ANEMOMETERS (meter)
WIND SPEED AT 15 METER (mps)
8.1
8.3
8.4
8.5
8.5
8.3
8.6
15
12
10/16
8
4
0927
1003
2
+.10
+.07
+.08
+.07
+.07
+.07
+.07
RICHARDSON NUMBER (Ri)

4. ANALYSIS OF THE WIND STRESS MEASUREMENTS

The digitized records from the anemometer-bivanes were summarized to obtain the conventional measures of the wind stress. As conventionally defined, the shearing stress,

$$\tau_{xz} = \overline{-\rho_a u'w'}$$

where

τ_{xz} = Shearing stress in the xz plane

ρ_a = air density

$u' = u - \bar{u}$

$w' = w - \bar{w}$

likewise

$$\tau_{yz} = \overline{-\rho_a v'w'}$$

where

$v' = v - \bar{v}$

The total stress is then defined as the sum

$$\tau_{total} = \tau_{xz} + \tau_{yz}.$$

Friction velocity is then

$$u_* = (\tau/\rho_a)^{1/2},$$

and drag coefficient

$$C_D = \left[\frac{u_*}{\bar{u}}\right]^2,$$

where C_D applies to the level at which $\bar{u}$ was measured. Averages were formed over 60 observation points or 30 seconds for purposes of defining the fluctuation terms. Values of total stress, friction velocity, and drag coefficient were computed for each 30 second period. These 30 second computations were later averaged over a period of 6 minutes resulting in the data included in Table 1.

TABLE 1. Wind stress and drag coefficients.

Date	Time	RMS Wave Hts. (Cm)	$\bar{u}_2$ $\left(\frac{Cm}{Sec}\right)$	$\bar{u}_{10}$ $\left(\frac{Cm}{Sec}\right)$	τ_2 $\left(\frac{dynes}{Cm}\right)$	τ_{10} $\left(\frac{dynes}{Cm}\right)$	u_{*2} $\left(\frac{Cm}{Sec}\right)$	$u_{*(10)}$ $\left(\frac{Cm}{Sec}\right)$	C_{d2}	C_{d10}	
9/24	1733	15.3	515.	568.	.214	.580	14.6	24.0	.00080	.00179	
	39	17.0	470.	524.	.363	.509	19.0	22.5	.00163	.00185	
	45	18.0	507.	572.	.247	.447	15.7	21.1	.00096	.00136	
	51	16.1	539.	593.	.301	.621	17.3	24.9	.00103	.00176	
	57	16.8	569.	621.	.321	.477	17.9	21.8	.00099	.00123	
	1803	17.6	580.	648.	.384	.284	19.6	16.8	.00114	.00067	
	09	19.7	562.	610.	.321	.286	17.9	16.9	.00101	.00076	
		17.2	534		.307	.458			.00108		Mean Value
9/24	2226	22.8	744.	983.	.423	.373	20.5	19.3	.00076	.00038	
	32	24.7	820.	1129.	.619	1.044	24.8	32.3	.00092	.00081	
	38	27.5	839.	1157.	1.086	1.494	32.9	38.6	.00154	.00111	
	44	26.7	826.	1123.	.715	1.038	26.7	32.2	.00104	.00082	
	50	27.2	807.	1130.	.794	.995	28.1	31.5	.00121	.00077	
	56	25.7	830.	1152.	1.011	.371	31.8	19.2	.00146	.00027	
			811		.778	.886			.00117		Mean Value
9/25	0716	25.3	673.	978.	.728	.832	26.9	28.8	.00160	.00086	
	22	26.5	676.	981.	.500	.265	22.3	16.2	.00109	.00027	
	28	23.8	641.	933.	.561	.331	23.7	18.2	.00136	.00038	
	34	26.6	575.	830.	.359	.091	18.9	9.5	.00108	.00012	
	40	27.4	602.	881.	.303	-.165	17.4	12.8	.00083	-.00021	
	46	25.9	482.	799.	.359	.344	18.9	18.5	.00154	.00053	
	52	24.2	552.	857.	.351	.013	18.7	3.6	.00115	.00001	
			600		.452	.244			.00124		Mean Value
9/25	1506	34.7	637.	819.	.318	.034	17.8	5.9	.00078	.00005	
	12	29.6	665.	871.	.487	.080	22.0	8.9	.00110	.00010	
	18	36.4	681.	874.	.394	.265	19.8	16.2	.00084	.00034	
	24	35.5	624.	791.	.328	.127	18.1	11.2	.00084	.00020	
	30	35.4	695.	857.	.523	-.121	22.8	11.0	.00108	-.00016	
	36	34.2	648.	824.	.325	.189	18.0	13.7	.00077	.00027	
	42	32.1	620.	796.	.651	.361	25.5	19.0	.00169	.00056	
			653		.432	.134			.00101		Mean Value
9/26	1026	12.4	517.	646.	.310	.119	17.6	10.9	.00115	.00028	
	32	11.9	474.	635.	.213	.025	14.6	5.0	.00094	.00006	
	38	10.9	584.	777.	.305	.271	17.4	16.4	.00089	.00044	
	44	12.1	543.	741.	.336	.142	18.3	11.9	.00113	.00025	
	50	12.7	621.	805.	.178	.175	13.3	13.2	.00046	.00026	
	56	11.6	545.	727.	.143	-.054	11.9	7.3	.00048	-.00010	
	1102	12.9	504.	683.	.335	.369	18.3	19.2	.00131	.00079	
		12.5	541		.260	.148			.00091		Mean Value

TABLE 1 (Continued)

Date	Time	RMS Wave Hts. (Cm)	$\bar{u}_2$ $\left(\frac{Cm}{Sec}\right)$	$\bar{u}_{10}$ $\left(\frac{Cm}{Sec}\right)$	τ_2 $\left(\frac{dynes}{Cm}\right)$	τ_{10} $\left(\frac{dynes}{Cm}\right)$	u_{*2} $\left(\frac{Cm}{Sec}\right)$	$u_{*(10)}$ $\left(\frac{Cm}{Sec}\right)$	C_{d2}	C_{d10}	
9/27	1126	10.9	264.	302.	.111	.036	10.5	6.0	.00159	.00039	
	32	11.2	259.	302.	.040	-.049	6.3	7.0	.00059	-.00054	
	38	10.2	288.	324.	.135	.031	11.6	5.6	.00163	.00029	
	44	11.8	288.	332.	.215	.009	14.6	3.0	.00259	.00008	
	50	11.8	307.	346.	.182	.136	13.4	11.6	.00192	.00113	
	56	11.4	296.	348.	.108	.141	10.4	11.8	.00123	.00116	
	1202	10.9	298.	356.	.148	.116	12.1	10.7	.00166	.00091	
	08	10.9	308.	369.	.188	.009	13.7	3.1	.00197	.00007	
	14	10.7	318.	388.	.189	.023	13.7	4.8	.00186	.00015	
	20	11.3	317.	386.	.164	.096	12.8	9.8	.00163	.00064	
			294		.148	.055			.00167		Mean Value
10/5	1646	10.2	422.	428.	.501	.094	22.3	9.7	.00280	.00051	
	52	10.4	452.	486.	.565	.238	23.7	15.4	.00276	.00100	
	58	11.3	434.	460.	.585	.043	24.2	6.5	.00310	.00020	
	1704	10.7	363.	389.	.301	.144	17.3	12.0	.00227	.00095	
	10	10.8	385.	435.	.546	.016	23.3	4.0	.00367	.00008	
	16	11.1	451.	494.	.401	-.078	20.0	8.8	.00197	-.00031	
	22	17.6	388.	407.	.260	.113	16.1	10.6	.00173	.00068	
			414		.451	.081			.00261		Mean Value

TABLE 1 (Continued)

Date	Time	RMS Wave Ht. (Cm)	$\overline{U}_4$ $\left(\frac{Cm}{Sec}\right)$	$\overline{U}_2$ $\left(\frac{Cm}{Sec}\right)$	τ_4 $\left(\frac{dynes}{Cm^2}\right)$	U_{*4} $\left(\frac{Cm}{Sec}\right)$	C_{d4}	C_{d2}	
10/8	1212	18.9	568.		.386	19.6	.00119	.00134	
	18	18.7	622.		.386	19.1	.00094	.00104	
	24	18.4	778.		.445	21.1	.00073	.00080	
	30	20.4	689.		.372	19.2	.00078	.00085	
	36	20.4	623.		.385	19.6	.00099	.00109	
	42	17.0	508.		.251	15.8	.00097	.00107	
	48	18.0	541.		.235	15.3	.00080	.00087	
	54	18.9	565.		.249	15.7	.00078	.00084	
			612.	589.		15.6		.0010	Mean Value
10/8	1522	16.6	236.		.052	7.2	.00094	.00102	
	28	18.0	250.		.051	7.1	.00082	.00090	
	34	17.8	220.		.026	5.1	.00054	.00058	
	40	16.2	249.		.051	7.1	.00083	.00089	
	46	17.6	274.		.012	3.5	.00016	.00017	
	52	18.7	254.		.032	5.7	.00050	.00052	
			247.	238.		5.9		.00068	Mean Value
10/9		45.3	1110.		2.524	50.2	.00204	.00240	
		42.4	1046.		1.640	40.4	.00149	.00168	
		43.5	1096.		1.472	38.2	.00122	.00136	
			1084.	1020.				.00181	Mean Value
10/10	0947	33.7	636.		.323	17.9	.00079	.00087	
	53	32.7	653.		.584	24.1	.00136	.00152	
	59	38.0	706.		.455	21.3	.00091	.00100	
	1005	36.2	663.		.478	21.8	.00108	.00120	
	11	36.4	640.		.216	14.6	.00052	.00056	
	17	36.4	602.		.496	22.2	.00136	.00153	
			650.	620.				.00111	Mean Value
10/10	1522	24.2	466.		.253	15.9	.00116	.00130	
	28	20.2	462.		.241	15.5	.00112	.00126	
	34	26.1	368.		.093	9.6	.00069	.00074	
	40	23.7	441.		.281	16.7	.00144	.00161	
	46	21.1	404.		.117	10.8	.00072	.00077	
	52	20.5	418.		.312	17.6	.00178	.00205	
			429.	405.				.00129	Mean Value
10/11	1113	7.3	765.		.326	18.0	.00055	.00060	
	19	8.6	820.		.356	18.8	.00052	.00057	
	25	6.4	800.		.321	17.9	.00050	.00054	
	31	8.7	875.		.894	29.8	.00116	.00129	
	37	8.7	908.		.484	22.0	.00058	.00064	
	43	8.4	864.		.925	30.4	.00123	.00140	
	49	9.8	806.		.378	19.4	.00058	.00063	
				771.				.00090	Mean Value

TABLE 1 (Concluded)

Date	Time	RMS Wave Ht. (Cm)	$\bar{U}_4$ $\left(\frac{Cm}{Sec}\right)$	$\bar{U}_2$ $\left(\frac{Cm}{Sec}\right)$	τ_4 $\left(\frac{dynes}{Cm}\right)$	U_{*4} $\left(\frac{Cm}{Sec}\right)$	C_{d4}	C_{d2}	
10/11	1341	14.8	811.		.767	27.6	.00116	.00128	
	47	14.6	740.		.715	26.7	.00130	.00145	
	53	14.7	755.		.526	22.9	.00092	.00100	
	59	15.2	727.		.463	21.5	.00087	.00096	
	1405	14.3	734.		.542	23.2	.00100	.00110	
	11	13.2	699.		.306	17.4	.00062	.00067	
			744.	709.		23.2		.00107	Mean Value
10/16	0933	9.3	601.		.464	21.5	.00128	.00143	
	39	10.1	635.		.501	22.3	.00124	.00137	
	45	10.0	670.		.559	23.6	.00124	.00137	
			635.	601.		22.5		.00139	Mean Value

Data included in Table 1 show the RMS value of the water surface fluctuation, the average wind speeds at the specified height, the shear stress at the indicated levels, the friction velocity at the same levels, and drag coefficients. In cases where only one anemometer-bivane was used, at 4 meters, drag coefficients have been calculated for the two meter level assuming a logarithmic wind speed profile.

Within the, as yet not completely defined, limitations of the anemometer-bivane, the above data can be examined in terms of relationship discussed in the introduction. Analysis of the spectra of waves and turbulent flow have not been completed but a measure of water surface roughness is given by the RMS variability.

4.1. WIND STRESS VARIABILITY WITH HEIGHT ABOVE SURFACE

Boundary layer models are based on the assumption that there exists a layer in which the shearing stress is essentially independent of height, see for example Lumley and Panofsky (1964). In the present measurement program, several cases were available where direct measurement of the stress have been made simultaneously at two levels.

The cases for the period September 24-26 may be examined as an example. This series of measurements were conducted through a single storm system with no change in instrumentation. Bivanes were mounted at 2 and 10 meters on the tower and the data recorded in periods of about 45 minutes duration each. All periods were processed in identical manner.

It will be noted that for the two periods, 24 September, 1727-1819 and 2220-2300, the stress measured at the upper level exceeds that at the lower level by a significant amount. On the following morning the stress difference had changed and the upper level indicated values less than the lower. This condition prevailed throughout the remaining three periods. The differences in stress measured at the two levels was greater than 100% for the case of 25 September, 1500-1541.

This height variation of stress is not explained. The bivane is expected to attenuate the higher frequency components of the velocity fluctuation and should, therefore, give measurements of stress somewhat smaller than true values. It would be expected that the higher frequencies would contribute more to the total stress at the lower levels. If attenuation were the cause of the height dependency, it would be expected that the lower level would suffer the greater error and would indicate a smaller value than the higher. Since this was not observed in all cases, the bivane attenuation does not offer an explanation.

The prevailing weather patterns changed somewhat during the period. Wind direction shifted between observations but remained off the lake in all cases.

Stability varied from slightly unstable to somewhat more unstable during later observations. This small change in stability does not appear to be a logical cause of height variability. Until more investigation can give explanation to the large height variability of measured stress, it seems to appear that the assumption is not valid in this case.

4.2. SHEAR STRESS RELATED TO WAVE HEIGHT AND WIND SPEED

In previous work, see Elder and Soo (1967), wind profile estimates of shear stress were used to show a relationship between wind speed at a given height, wave height, and friction velocity. Only a few estimates were available during near neutral conditions. In the present study, stress measurements were made by direct observations so that we need not be restricted to the neutral case. These data were examined for similar relationships.

Over a rigid surface, the wind stress or drag is closely related to the wind speed since the surface features do not respond to the wind and therefore retain a constant "roughness." A water surface responds to the wind stress adjusting the surface character until equilibrium is attained as a "full sea" condition. It might be expected that under such equilibrium conditions, a constant relation between wind speed and stress would again attain for a given stability. It is, however, difficult or in most cases impossible to determine the degree of equilibrium during any given period of measurements. It is this author's opinion that this uncertainty accounts for much of the variability in reported results.

The computed friction velocities have been entered on Figure 6 as functions of wind speed and wave height as measured by the RMS surface variation. The observations are not completely comparable but are grouped to obtain a wider range of observations. Some of the data are measured at 2 and some at 4 meters above the mean surface which may be of importance in view of the earlier discussion.

The data show a wide variability but indicate a general increase in u_* with both wind speed and wave height. However, for a given wind speed category, u_* appears to reach a maximum and then decrease. The same tendency is noted for a given wave height category, particularly in the 10-15 cm class.

It might be assumed that the data represent random degrees of equilibrium in the samples obtained and that a least squares regression could give a true relationship to be expected under equilibrium. However, if a bias were to favor certain conditions, large errors would result. This appears to be the case near the extremes or at low wind speeds where few observations are available.

More observations under small waves and strong winds could give indication of the drag contribution of the small waves. If large values of stress are

RMS WAVE HEIGHT (CM)	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000	1000+
35+							**19.3** 19.8 18.1 21.8 14.6 22.2	**22.0** 22.8 21.3			**42.9** 50.2 40.4 38.2
30-35							**20.6** 17.8 18.0 22.5 17.9 24.1				
25-30				**9.6** 9.6	**18.9** 18.9	**18.9** 18.9	**22.1** 26.9 22.3 17.4 22.0		**29.9** 32.9 26.7 28.1 31.8		
20-25					**15.3** 15.9 15.5 16.7 10.8 17.6	**18.7** 18.7	**21.3** 23.7 19.2 19.6	**20.5** 20.5	**24.8** 24.8		
15-20			**5.9** 7.2 7.1 5.1 7.1 3.5 5.7		**17.6** 19.0 16.1	**16.9** 14.6 15.7 17.3 17.9 19.6 17.9 19.6 15.8 15.3 19.7	**19.1** 19.1	**21.1** 21.1			
10-15			**10.7** 10.5 6.3 11.6 14.6 10.4	**15.2** 13.4 12.1 13.7 13.7 12.8 17.3 23.3	**21.0** 22.3 23.7 24.2 20.0	**16.7** 17.6 17.4 18.3 11.9 18.3	**13.3** 13.3				
5-10											
0- 5											

WIND SPEED (CM/SEC.)

Figure 6. Friction velocity vs. wave height vs. wind speed.

observed in this case, it would indicate that drag is created by small waves prior to the development of long fast moving waves.

Figure 7 is a graph of drag coefficient at 2 meter elevation vs. mean wind speed for the anemometer-bivane measurements. Observations actually made at 4 meters have been reduced to 2 meter equivalent assuming a logarithmic wind speed profile. The data are entered as points for the individual 6 minute observations and large circled points for averages over approximately 40 minutes.

Inspection of the graph reveals a strong clustering of the data with some scattered points. It would suggest, as in the prior discussion, that the clustered data represent equilibrium conditions and that the scatter results from measurements under nonequilibrium. A time history of the wind and waves has not been obtained for the individual cases but it is of interest to note differences in the wave height for similar wind speeds where the drag coefficients differ. Two of the 40-minute average points offer such comparison.

Two cases for wind speeds of about 540 cm sec^{-1} indicate different values of drag coefficient. The case for 24 September, 1727-1819 has a mean wind speed equal to 534 cm sec^{-1} and drag coefficient of $1.08X10^{-3}$ while 26 September, 1020-1100 has mean wind equal to 541 cm sec^{-1} and drag coefficient of $0.91X10^{-3}$. RMS wave height for the former case was 17.2 cm while the later was 12.5. The earlier case having greater waves may indicate an equilibrium condition while waves were building in the later case.

The cases with wind speed near 750 cm sec^{-1} show a similar increase in drag for larger waves. 11 October, 1107-1149 having wind speed of 771 cm sec^{-1} and drag coefficient of $0.90X10^{-3}$ has an RMS wave height of only 8.3 cm while 11 October, 1335-1415 having a mean wind of 744 cm sec^{-1} and drag coefficient of $1.07X10^{-3}$ has an RMS wave height of 14.5 cm. These wave heights were measured with a pressure sensor and cannot be compared directly with the previous set but they do indicate increased drag for larger waves.

The data shown in Figure 7 have not been grouped with regard to stability and some of the scatter may be a result of buoyancy influences. It is, however, interesting to note the character of the relationship indicated by the clustered data assuming that these data may represent conditions of equilibrium.

It is noted that very small values of drag are observed for wind speed less than 250 cm sec^{-1} with a rapid increase reaching a maximum between 350 and 400 cm sec^{-1}. There appears to be a region of approximately constant drag coefficient of about $1.5X10^{-3}$ between 500 and 900 cm sec^{-1} after which a slight increase is observed. The points at higher wind speeds are based on few data and cannot, therefore, be considered strongly significant.

The reason for the abrupt increase in drag at about 250 to 300 cm sec^{-1} as compared to the gradual increase or constant values proposed by others is not clear. One could postulate that this increase corresponds to the development

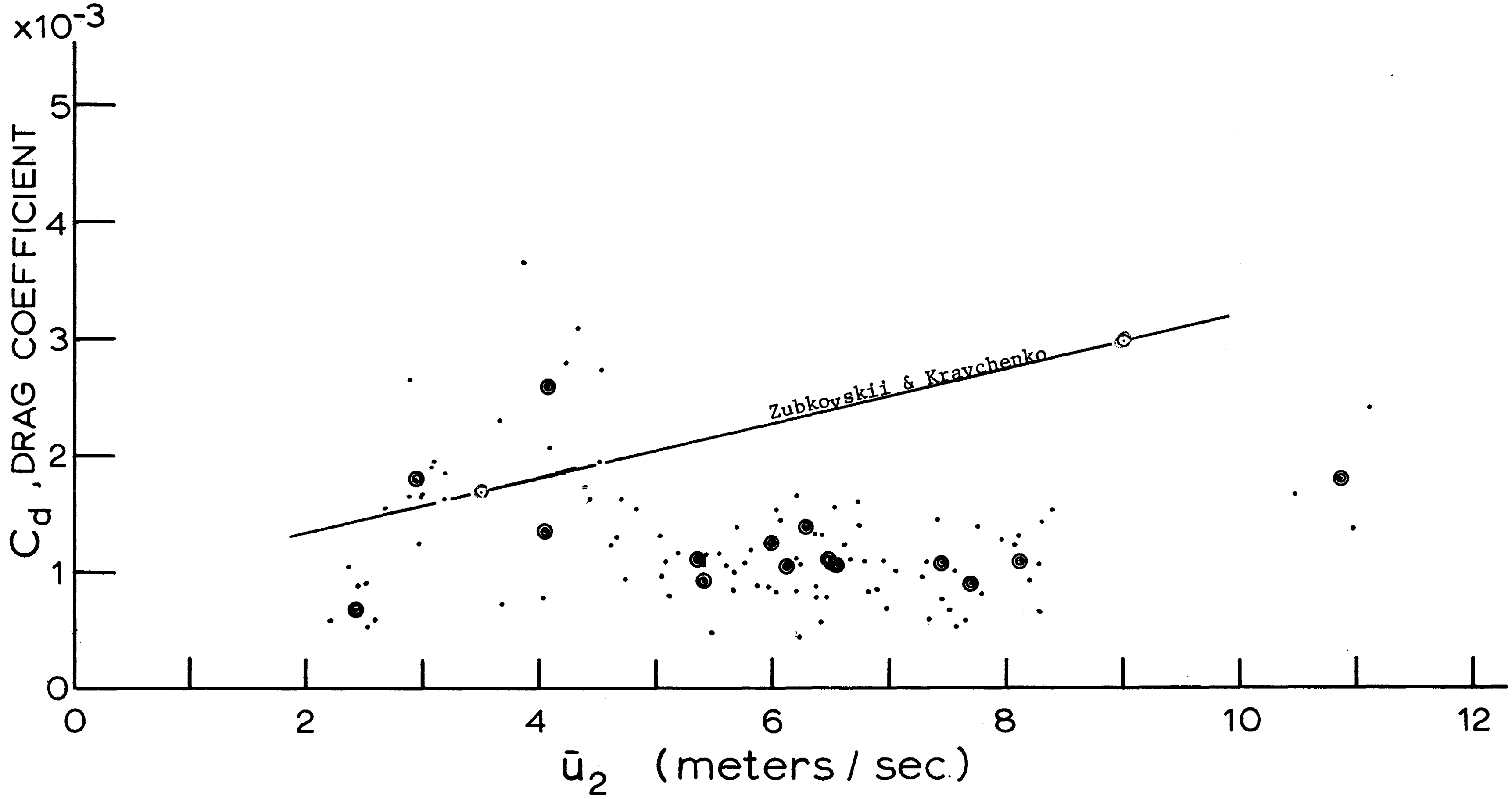


Figure 7. Drag coefficient at 2 meter vs. wind speed.

of surface ripples and the onset of "rough" flow. An explanation of this type has been advanced by Takahashi (1958) using friction velocity as wind criteria. He proposes a critical friction velocity of only 3.7 cm sec^{-1} whereas a value of about 11 cm sec^{-1} is observed in this case.

4.3. COMPARISON OF WIND STRESS MEASURED BY DIRECT MEANS AND PROFILE MODELS

For those periods when the wind profiles were logarithmic or closely approximate logarithmic, we can calculate the friction velocity (u_*) using the 15 meter and 4 meter wind speeds.

$$u_* = \frac{(u_2-u_1)k}{\ln(\frac{z_2}{z_1})}$$

where

u_* = Friction velocity

k = Von Karman Constant

These values can then be compared to the ones obtained by the anemometer-bivanes (Table 2). The result is plotted in the scatter diagram (Figure 8). Three profile periods of September 25, October 5, and October 10, were questionable because of the 4 meter anemometer malfunction on September 25 and the strongly nonlogarithmic features of the October 5 and October 10 data. With these three sets of values not included we obtain a linear correlation coefficient, r = 0.84 between the $u_{*bivane}$ and $u_{*profile}$ values. The least square regression gives us $\bar{u}_{*profile} = -0.4 + 1.15\ \bar{u}_{*bivane}$ for 74 sets of values. With data from October 5 and October 10 period included, we obtain

$$r = 0.79$$

and

$$u_{*profile} = -0.3 + 1.13\ u_{*bivane}$$

for 87 sets of values. Both values of r obtained are definitely significant for the sample sizes used. It therefore appears that if the anemometer-bivane measurements are taken as valid, the wind speed profile will give comparable measurement of the surface stress if averaged over many cases. However, any specfic measure obtained from shorter period averages may differ by a factor of as much as two.

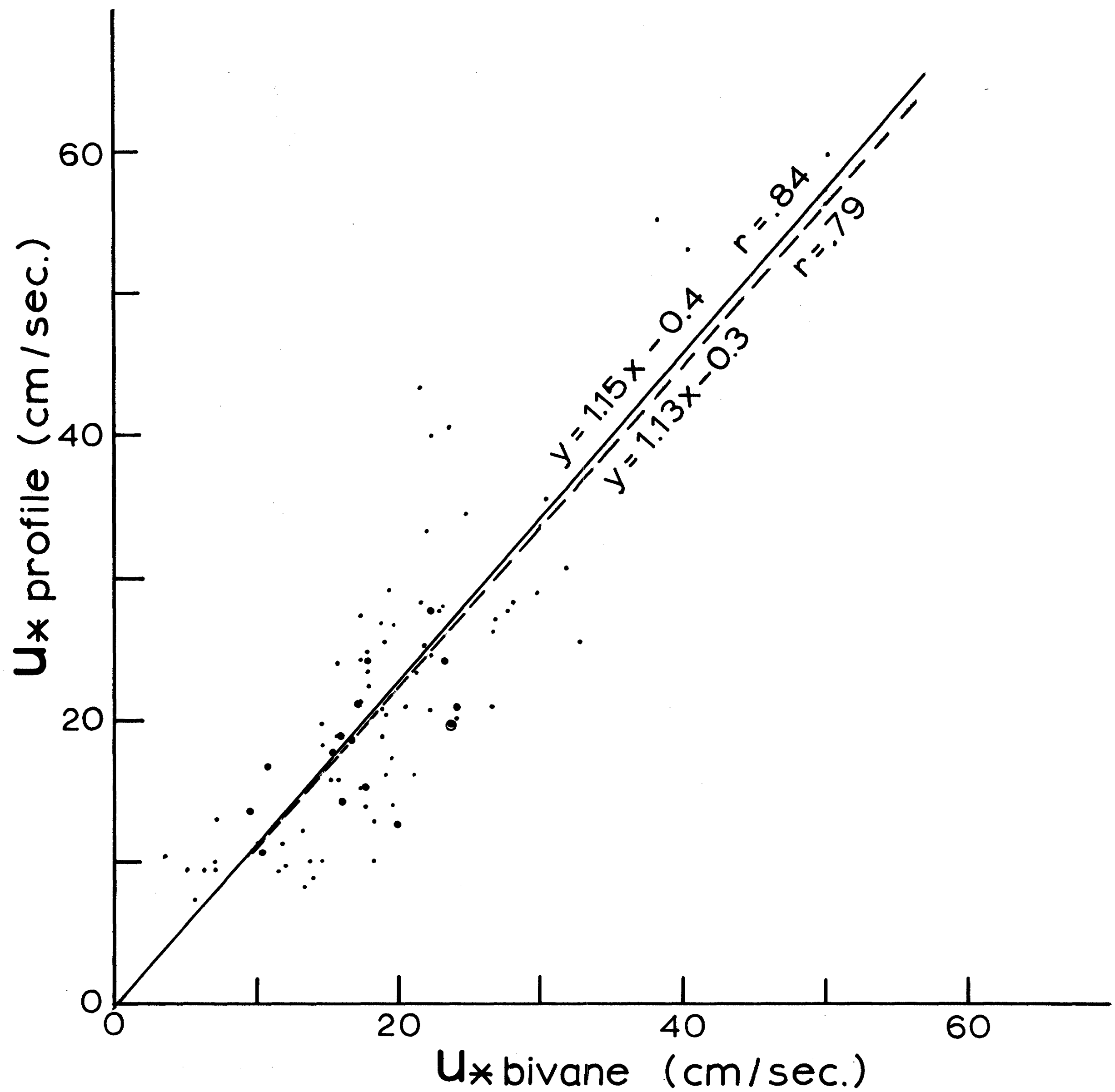


Figure 8. $u_{*profile}$ vs. $u_{*bivane}$.

TABLE 2. Comparison of friction velocities.

DATE	TIME	u_{*2}	u_{*p}
9/24	1733	14.6	18.2
	39	19.0	25.5
	45	15.7	23.9
	51	17.3	27.3
	57	17.9	23.3
	1803	19.6	26.7
	09	17.9	24.2
9/24	2226	20.5	20.9
	32	24.8	34.5
	38	32.9	25.5
	44	26.7	20.9
	50	28.1	28.2
	56	31.8	30.6
9/25	0716	26.9	27.0
	22	22.3	24.5
	28	23.7	19.7
	34	18.9	20.6
	40	17.4	21.2
	46	18.9	18.8
9/26	1026	17.6	13.9
	32	14.6	10.0
	38	17.4	15.2
	44	18.3	12.7
	50	13.3	12.1
	56	11.9	11.2
	1102	18.3	10.0
9/27	1126	10.5	10.6
	32	6.3	9.4
	38	11.6	9.4
	44	14.0	8.8
	50	13.4	8.2
	56	10.4	10.6
	1202	12.1	9.7
	08	13.7	10.0
10/5	1646	22.3	27.6
	52	23.7	19.7
	58	24.2	20.9
	1704	17.3	21.2
	10	23.3	24.2
	16	20.0	12.7
	22	16.1	14.2

DATE	TIME	u_{*4}	u_{*p}
10/8	1212	19.6	17.3
	18	19.1	16.1
	24	21.1	16.1
	30	19.2	20.3
	36	19.6	13.9
	42	15.8	15.8
	48	15.3	15.8
	54	15.7	18.8
10/8	1522	7.2	13.0
	28	7.1	9.4
	34	5.1	9.4
	40	7.1	10.0
	46	3.5	10.3
	52	5.7	7.3
10/9	2325	50.2	59.7
	31	40.4	53.0
	37	38.2	55.2
10/10	0947	17.9	24.2
	53	24.1	20.0
	59	21.3	23.3
	1005	21.8	25.2
	11	14.6	19.7
	17	22.2	20.6
10/10	1522	15.9	18.8
	28	15.5	17.6
	34	9.6	13.6
	40	16.7	18.5
	46	10.8	16.7
	52	17.6	15.2
10/11	1113	18.0	22.4
	19	18.8	26.7
	25	17.9	24.8
	31	29.8	28.8
	37	22.0	33.3
	43	30.4	35.5
	49	19.4	29.1
10/11	1341	27.6	27.6
	47	26.7	26.1
	53	22.9	27.6
	59	21.5	28.2
	1405	23.2	27.9
	11	17.4	24.2
10/16	0933	21.5	43.3
	39	22.3	40.0
	45	23.6	40.6

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